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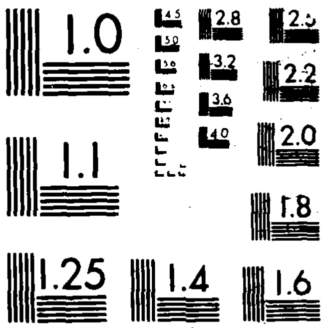
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Test Methodology for Adaptive Antenna Systems

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Conventional antenna evaluations to determine gain, pattern, polarization, and terminal impedance characteristics are conducted on a component level. Adaptive antenna evaluations extend conventional antenna evaluations to system-level tests that quantify the performance of a receiving antenna system in both interference-free and interference environments. Test procedures for conventional antenna evaluations are well established. Test procedures for adaptive antennas expand the scope of antenna testing, tend to

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be system specific, and represent particular scenarios for interference. Adaptive antenna evaluations require additional instrumentation having more general spectral capabilities than conventional antenna test equipment, as well as an rf measurement facility capable of simultaneously generating both desired and interference signal components arriving from differing directions. The expansion of antenna testing for adaptive antenna designs is reviewed.

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FIGURES

I. INTRODUCTION

Adaptive antenna processing techniques are evolving from research to operational systems. The development of operational adaptive systems and test techniques to evaluate those systems should be pursued concurrently. The evaluation of conventional antenna designs is well established, and standards for such measurements are well known and documented.[1] To date, unfortunately, standards for adaptive antenna testing do not exist; moreover, adaptive antenna tests tend to be system specific, and each application is tied to a particular scenario for interference. Additional requirements for adaptive antenna evaluations are reviewed.

Adaptive antenna designs operate in the receive mode and use correlation circuitry to cancel interference dynamically. The adaptive antenna maximizes the SINR (signal-to-interference-plus-noise ratio). There are two broad classes of adaptive antenna designs: (1) fully adaptive arrays[2] combine individual array elements to maximize the SINR by using properties of the desired signal, such as spectral characteristics, signal level, and source direction, to distinguish the desired signal from the interference, and (2) adaptive sidelobe canceller designs[3,4] combine a main antenna, which receives the desired signal, with lower-gain auxiliary antenna elements that subtract the interference power received in the sidelobe structure of the main antenna.

The operation of an adaptive antenna can be interpreted from two equivalent viewpoints. The spatial interpretation of adaptive interference cancellation is the generation of a null in the overall antenna system pattern in the direction of the interference. The circuit interpretation of adaptive interference cancellation is the combination of several antennas to minimize interference signals at the receiver input. Progress in the development of adaptive antenna systems has been reviewed in "Special Issues" of the *IEEE Transactions on Antennas and Propagation*.[5,6,7] These special issues provide an interesting evolutionary study of adaptive antenna technology and concepts. The *Proceedings of the IEEE* and the *IEEE Transactions on Aerospace and Electronic Systems* have also provided forums for adaptive processing technology.

II. ADAPTIVE ANTENNA TEST FACTORS

Conventional antenna test procedures concern component-level parameters including gain, pattern, polarization, and terminal impedance values. While conventional component-level antenna parameters still require evaluation in adaptive antenna designs, the effectiveness of the adaptive antenna in reducing interference must also be measured. Conventional antenna measurements are typically made at a limited number of frequencies over the operating bandwidth, but adaptive antenna testing measures interference cancellation over the entire bandwidth. The receiver can be separated from the antenna in conventional antenna testing, but the noise contributions from the adaptive circuitry, as well as the residual uncancelled interference, must be included in an adaptive antenna evaluation. Conventional antennas are generally viewed as linear passive components, but adaptive cancellation has a limited dynamic range. These additional requirements for adaptive antenna evaluations will be discussed below.

Adaptive antenna designs should be initially measured in an interference-free environment. Such measurements provide a baseline reference for subsequent measurements that include interference, and the measured performance of the entire receiving system can be compared to that projected from the individual component-level values. When testing proceeds to measurements including interference, the levels, spectral characteristics, locations, and deployment of the interference are selected from a scenario developed for the system's application. The scope of an adaptive antenna test program therefore extends from antenna and receiver component parameters to system-level tests in the presence of interference; these more complex tests naturally require more test equipment and facility capability than conventional antenna testing. The distinction between conventional and adaptive antenna testing is illustrated in Fig. 1.

A. ANTENNA MODELING REQUIREMENTS

Both conventional and adaptive antenna evaluations measure a response comprised of the radiation mechanisms of the antenna and its surrounding environment. Conventional measurements determine the antenna's response at discrete frequencies over the operating bandwidth, and measurement accuracy is

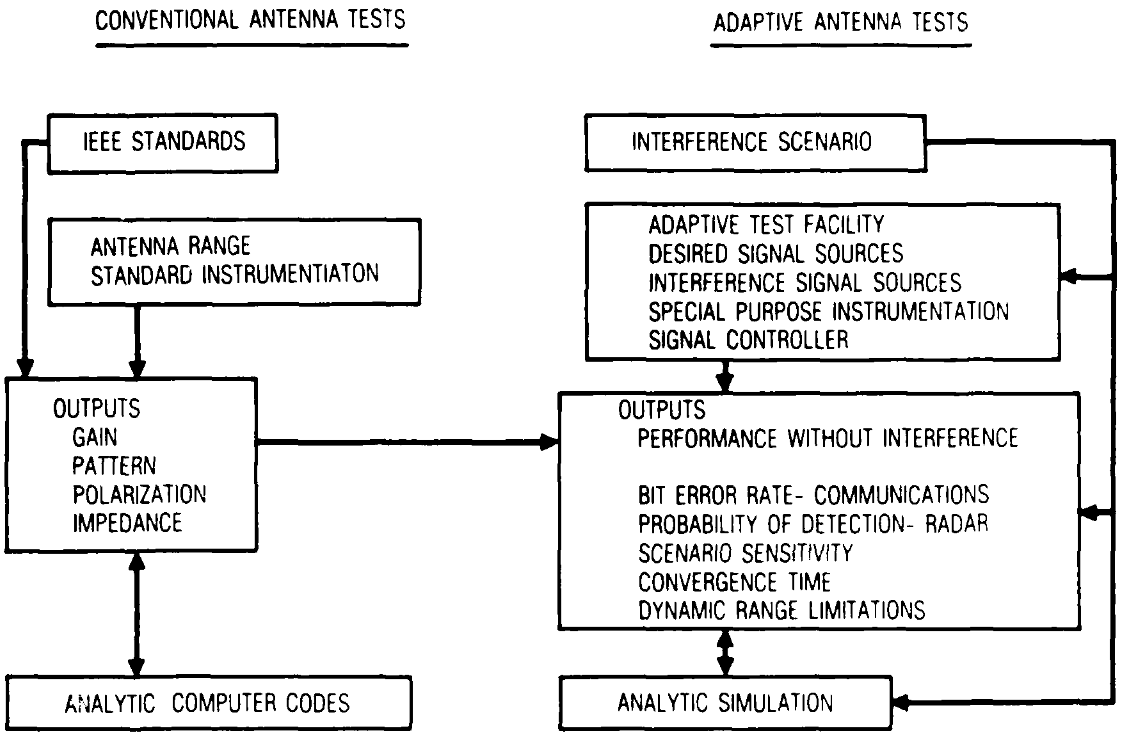

Fig. 1. Comparison between Conventional and Adaptive Antenna Testing

limited by the ability to measure the narrowband phasor sum of the individual radiation mechanisms. Adaptive antenna testing, however, measures variations in interference cancellation over the full spectrum of the operating bandwidth, and measurement accuracy here depends not only on the phasor sum of the individual radiation mechanisms, but also on the manner in which those phasor components are subtracted to cancel interference over the operating bandwidth. Adaptive antenna testing will be shown to be more sensitive to the low-level components in the antenna response than are conventional antenna measurements; this added sensitivity results in more stringent requirements for modeling in the adaptive antenna case. In this discussion, modeling refers to the required simulation of both the antenna itself and its installation effects.

An example will be used to clarify the above-mentioned "low-level components in the antenna response." Antenna systems mounted on aircraft, as shown in Fig. 2, are influenced by the surrounding airframe. The phasor sum of the antenna response consists not only of components from the antenna itself but

also those components scattered from the wings, the stabilizer, and other portions of the airframe. In a properly designed antenna installation, these scattering components make a minor contribution to the antenna response in the desired coverage area of the antenna. With conventional antenna testing, only a small portion of the entire airframe surrounding the antenna installation is required if one wishes to model the airframe's effects on the antenna coverage characteristics. Measurements using a small portion of the airframe are very attractive for reasons of cost and handling, and they also reduce the size of the measurement facility. It will be shown, however, that adaptive antenna designs are significantly influenced by the low-level components; moreover, as interference can arrive from beyond the desired coverage area, more extensive modeling is required.

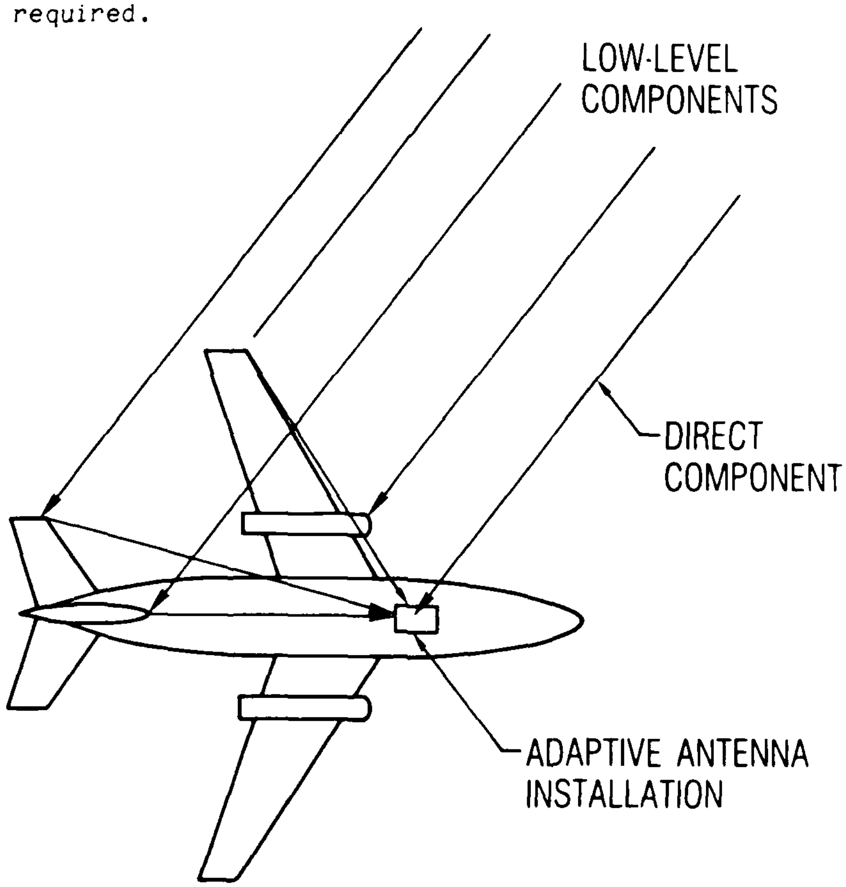

Fig. 2. Effects of Installation on Aircraft Antennas

A key question concerns determining that portion of the airframe which needs to be modeled in the antenna measurements. For aircraft applications, existing computer codes can be used to determine the values of the individual

radiation components; examples of these codes and their experimental validation are given in Refs. 8 and 9. The codes analyze the interactions between the antenna and the airframe by determining the levels of the individual radiation components in the desired coverage area. The portion of the airframe to be modeled can be determined from the measurement inaccuracy that results from deleting the radiation component. As indicated in Fig. 1, analytic projections of antenna performance are exceedingly useful in determining requirements for measurements.

The sensitivity of the measurement accuracy to the low-level components will be contrasted for both conventional and adaptive antenna testing. A simple representation of the antenna system will be used. Two radiation sources, which are physically separated, are assumed. One source, having a unit amplitude, represents the main response of the antenna; the second source, having a relative amplitude a and phase α, represents a low-level component, such as the scattering from a wing.

For conventional antenna testing, the measured antenna response is the phasor sum of the components. As is well known, the amplitude of the total field becomes

$$A = (1 + a^2 + 2a \cos\alpha)^{1/2} \tag{1}$$

and the phase of the total field becomes

$$\phi = \tan^{-1} [a \sin\alpha/(1 + a \cos\alpha)] \tag{2}$$

The effect of a low-level component is assessed by comparing the total field values with 1 for the amplitude and 0° for the phase, the latter being the measured values when the low-level component is not present. For example, if the relative value of a is -30 dB, the peak-to-peak error in the amplitude is 0.56 dB and the peak-to-peak error in the phase is 3.5°. Generally, such errors are acceptably low for most test programs, and simulation with the requisite increase in antenna modeling for the low-level component is not required. The effect of the low-level components for other values of a, as well as the statistics of the variations (assuming α is equally likely and uniformly distributed from 0 to 360°), may be found in Ref. 10.

The low-level components result in a more dramatic effect on adaptive antenna cancellation performance. In an adaptive system, not only the relative amplitude and phase of the low-level components but also their phase rates associated with physical separation must be considered. The phase rates of the components are important because adaptive cancellation must be achieved over a bandwidth. When interference is strong, the output SINR is maximized by minimizing the interference power and accepting the increase in thermal noise associated with the adaptive circuitry. The interference can be ideally cancelled at a center frequency, but when the frequency varies from the center frequency, the interference is no longer ideally cancelled.

The same simple antenna model used to illustrate the effect of low-level components on conventional antenna testing will be used for the adaptive antenna analysis. This model is described in Fig. 3, where the low-level component is physically displaced from the main antenna and has a relative amplitude a and phase angle α. The low-level component is shown in a dashed form; this antenna representation is identical to that used in the analysis given in Eqs. (1) and (2). The adaptive system uses a third point source as a cancellation antenna separated from the other two. The output of this cancellation antenna is controlled by the adaptive circuitry to provide a net amplitude b and phase β, relative to the main antenna, to cancel the interference. The interference power can be expressed as

$$\begin{aligned} |\varepsilon|^2 = 1 &+ a^2 + b^2 \\ &+ 2a \cos\alpha - 2b \cos\beta \\ &- 2ab \cos(\alpha - \beta) \end{aligned} \tag{3}$$

using the parameters described in Fig. 3. The adaptive circuitry sets this quantity to 0 at a center frequency f_0, so b and β, the adaptive weighting values, can be determined. In this simple example only one null, or degree of freedom, is assumed; i.e., several weights can be used to generate a "notch" null having more bandwidth with a corresponding increase in circuit complexity.

Next, the interference power is calculated as the frequency changes, with the adaptive weight fixed at the value determined by

$$\begin{aligned} \alpha &= \alpha_0 + A\Delta f \\ \beta &= \beta_0 + B\Delta f \end{aligned} \tag{4}$$

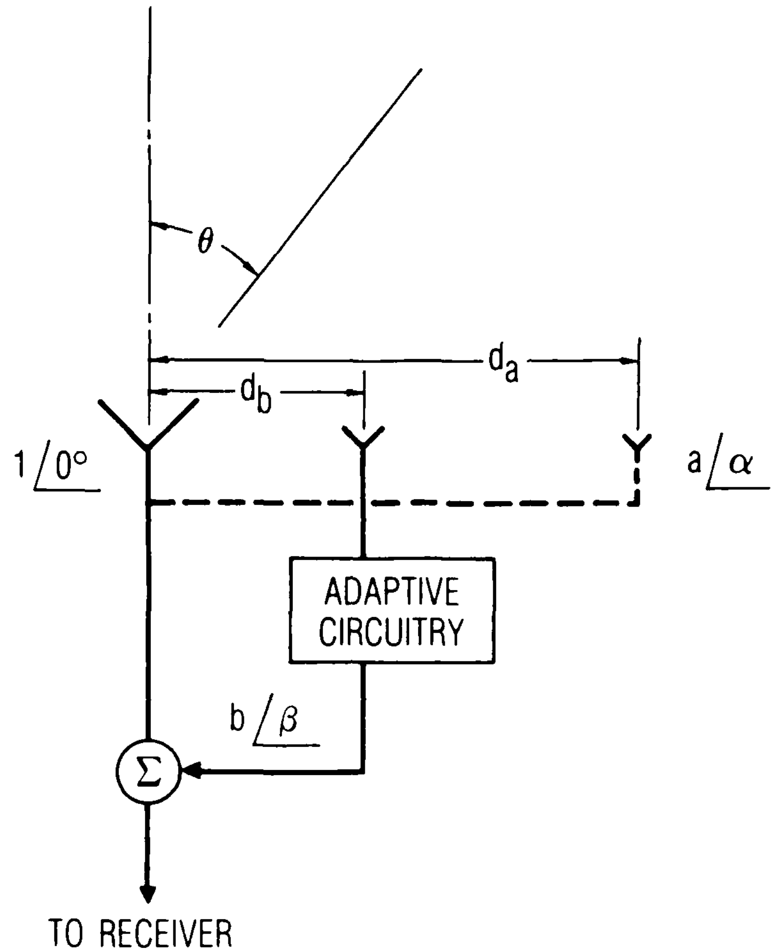

Fig. 3. Adaptive Antenna Model with Low-Level Component

where α_0 and β_0 are the phase values at the center frequency f_0, Δf is the deviation from the center frequency, and A and B are the phase rates corresponding to the physical separation of the sources projected in the direction of the interference arrival (defined by θ). Thus, the value of A for the low-level component is $k_0 d_a(\cos\theta)/f_0$, using the parameters defined in Fig. 3. Similarly, the value of B is $k_0 d_b(\cos\theta)/f_0$. The values A and B physically represent the rate at which the phases of the low-level component and the adaptive cancellation antenna change with frequency relative to the main antenna output. After some algebra it can be shown that the output interference power becomes

$$|\varepsilon|^2 = 4 \{\sin^2(B\Delta f)/2 + a^2\sin^2[(A - B)\Delta f/2] - 2a \sin[(A - B)f/2] \sin(B\Delta f/2) \cos[(A\Delta f/2) - \alpha_0]\} \tag{5}$$

The first term in the above expression is the cancellation performance that occurs when the low-level component is not present and has been previously derived (Ref. 11). Notice also that the low-level component has importance only when its value is comparable to the desired cancellation performance. When the source of the low-level component is physically close to the adaptive cancellation element, the adaptive cancellation is unaffected. In this case the two phase rates, A for the low-level component and B for the cancellation element, are similar and the cancellation performance is dominated by the first term in Eq. (5). Differences in cancellation performance arise when the low-level source is separated from the remaining portion of the antenna system.

An example calculation, which uses the value a = -30 dB (previously used for the conventional antenna measurement), is shown in Fig. 4. These calculations assume the projections of d_a and d_b, corresponding to an interference arrival angle of θ, equal to 40 and 2 wavelengths, respectively. These calculations indicate the normal loss in cancellation performance as the operating bandwidth increases. The interference cancellation varies by several dB, depending on the value of α_0. By contrast, a component with a -30 dB level has an almost immeasurable effect on a conventional antenna measurement.

This simple analysis demonstrates that conventional antenna modeling may not be adequate for adaptive antenna evaluations. When the low-level components from the environment surrounding the antenna itself influence the antenna response at a level comparable to the desired cancellation performance, a more extensive model is required. In addition, because the interference may arrive from angles beyond the normal coverage area of the antenna, more extensive modeling may be required so that the received interference level is similar to levels that would be observed in an actual installation. In the case of aircraft installations, for example, the interference level may be reduced by blockage caused by the fuselage. Thus, in general, the modeling requirements are more severe for adaptive antenna testing than for conventional antenna testing.

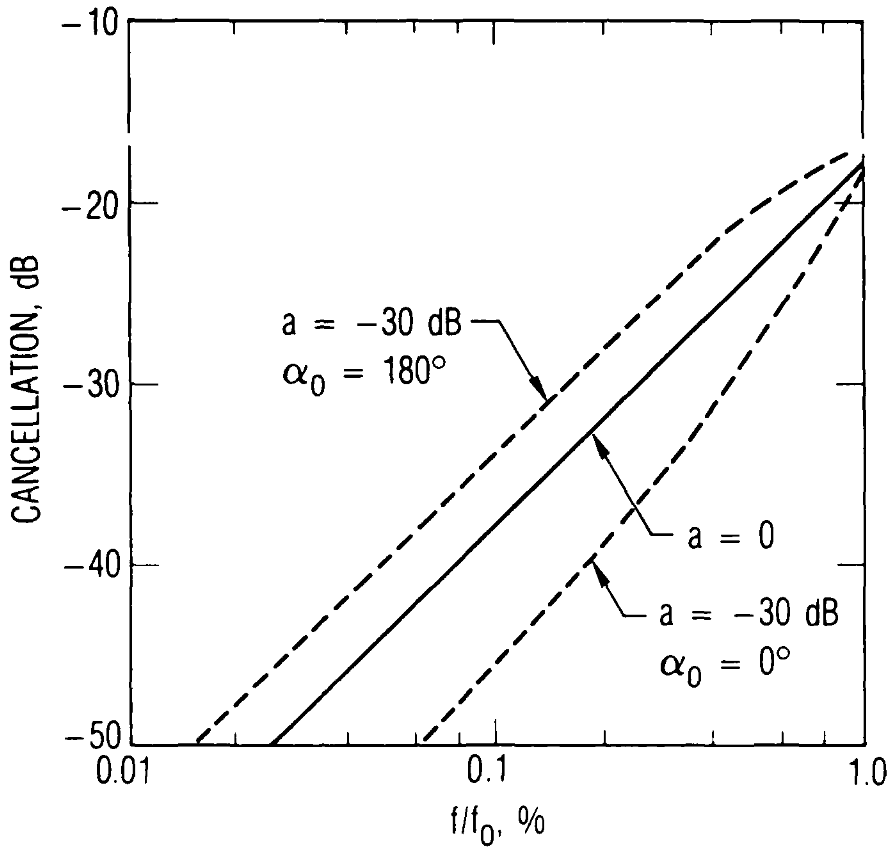

Fig. 4. Effect of Low-Level Component on Adaptive Cancellation

This analysis has been specifically applied to the requirements for modeling the antenna installation. The analysis can also be applied to determine the effects of multipath errors in the measurement facility. In this case, a represents the multipath level, and the phase rate is derived from the physical separation between the source of multipath and the adaptive antenna being measured.

While this discussion is concerned with measurement issues, the results of the analysis are also useful in making analytic projections of adaptive antenna performance. The antenna is often represented in adaptive system analyses as an isolated source; in reality, as shown both from measurements and in modern analytic programs, practical antenna designs have more complex responses. This simple two-point source representation of the antenna indicates the impact of the antenna design on adaptive system performance. A more specific analysis of the effects of the diffraction components in reflector

antennas has recently been published.[12] The individual radiation mechanisms of reflector antennas (e.g., feed radiation, edge diffraction, blockage, spillover, etc.) result in a collection of components whose levels vary with aspect angle. The low-level components in this collection function in the same way as the simple two-source analysis presented here; the individual radiation components of the antenna alone limit the cancellation bandwidth. Further research is required to understand the limitations on adaptive antenna system performance imposed by the design of the antenna itself.

B. SCENARIO CONSIDERATIONS

Conventional antenna testing establishes compliance with such component-level specifications as gain, pattern coverage, impedance, polarization, etc. Adaptive antenna testing requires not only conventional testing to assure performance without interference, but also additional testing to establish the effectiveness of interference cancellation. Adaptive system specifications are written in conjunction with a scenario of the interference environment in which the system must operate. This scenario also forms the basis for adaptive system testing in the presence of interference.

The key parameters in the interference scenario are the number of interference sources, their individual power levels and spectral characteristics, their angular separation and motion relative to the desired signals, and the timing strategies for deploying interference. This scenario reflects both anticipated characteristics for interference as well as strategies for its deployment. Unfortunately, these parameters are both hypothetical and subjective, and tend to vary during system development.

The analytic projection of adaptive interference performance is generally accomplished through a software Monte Carlo simulation. Such simulations are often used to derive design parameters for adaptive system hardware. These simulation programs can also guide adaptive system testing, and the resulting validation strengthens the usefulness of the simulation. Software Monte Carlo simulations can be readily accomplished in a cost-effective manner; however, a similar Monte Carlo approach to experimental evaluation would lead to an inordinate test time and exorbitant costs. The analytic Monte Carlo simulation is a useful tool for test planning, one that can be used to derive interference configurations that provide representative tests

of adaptive antenna performance. In this way a limited number of test configurations can be obtained for a cost-effective test program.

An experimental validation of the simulation program increases its usefulness. The simulation program can therefore be used in the same manner as analytic techniques are used in the experimental development of antennas. Analytic codes that project antenna performance are often used in trade-off studies to select the design parameters for experimental validation. As indicated in Fig. 1, the joint use of analytic and experimental techniques provides a means of test planning, as well as a better understanding of either antenna design or adaptive antenna systems.

While the adaptive system is designed to satisfy a particular scenario, the test program should also evaluate the bounds of the hardware performance. The use of simulation programs to identify worst-case interference environments is one way to determine the bounds; an increase in interference power levels or in the number of interference sources is a second way. Such increases define a system's sensitivity to scenario changes and thus determine the limitations of a particular adaptive design.

C. INSTRUMENTATION AND FACILITY REQUIREMENTS

The adaptive system under test must be illuminated with both the desired signal(s) and interference signals that have appropriate angular spacing, spectral characteristics, and power levels. By contrast, conventional antenna tests are conducted with general-purpose instrumentation and illumination by a single test source at low power levels. The instrumentation and test facility requirements are thus more demanding for adaptive antenna testing than for conventional antenna testing.

The spectral characteristics of both the desired and interference signals used in adaptive antenna evaluations differ from the continuous-wave (CW) or swept waveforms used in conventional antenna test programs. Operational waveforms are often required to represent the desired signal component. For example, an adaptive antenna designed for spread-spectrum communication should use the operational waveform and modem so that the system performance can be measured.

The interference signals should have the same varied compositions as would be anticipated operationally. Thus narrowband, wideband, and pulsed interference signals might be implemented in a test program. (Useful diagnostic information can also result from such tests.) Initial measurements without interference should be conducted to establish a baseline for testing with interference. Next, the system might be evaluated with CW interference signals, followed by broadband interference, etc. Adaptive antenna testing therefore requires not only more signal generators, but also more diversity in signal modulation than is used in conventional antenna tests.

In addition, adaptive antennas are typically configured to counter strong interference, and the required power output from the test signal generators exceeds that of conventional test sources. This increased signal power is required to establish the dynamic range that might be encountered operationally. An important test parameter is the dynamic range over which adaptive processing is effective. At the present time, computers are an effective way to control the individual signal generators, their levels, and the timing for interference sources.

Facility requirements for adaptive system testing are also more demanding than those for conventional antenna testing. Conventional antenna tests are typically conducted with a single illuminator, and the test antenna is rotated to measure its angular variations in performance (conventional antenna test facilities are described in Ref. 1). Adaptive antenna testing requires that the system under test be illuminated by both desired and interference signal components. In addition, the desired signal and interference must be generated in such a manner that they arrive from different directions; by contrast, conventional antenna testing is conducted in a facility wherein a single test signal is generated. Adaptive test facilities therefore require more flexibility than conventional ones in order to generate test signals that arrive from different directions.

A typical assumption is that interference can arrive from any arbitrary direction. Conventional test facilities have varying ability to generate simultaneously test signals that arrive from different directions. For example, while tapered anechoic chambers have limited ability to vary the illumination direction, outdoor facilities offer more flexibility to establish such illumination. When desired and interference signals are confined to a limited

angular region, a collection of antenna elements appropriately fed by independent signal generators provides an effective test system.

When adaptive antenna systems for radar applications are evaluated, additional factors arise. Targets such as corner reflectors can be used both as test targets and calibration sources. The signal-to-noise ratio observed from a corner reflector with and without interference provides an effective measure of adaptive system performance. Interference is typically provided by independent generators; however, the radar receives not only the interference signal but also the radar return from the equipment generating the interference signal. The radar return from the equipment generating the interference can be measured by the radar under evaluation with the interference turned off. The radar return from the equipment should be compared with the level generated by the interference. Finally, measurements of interference beyond the range interval containing the desired target should be conducted to determine the inherent interference reduction provided by the range gating. In this case the range to the interference source should be varied to measure the range gate performance.

Multipath errors generated by the test facility have a greater effect on adaptive antenna testing than on conventional antenna testing. Multipath contributions of the test facility function as an additional interference source and consume additional degrees of freedom from the adaptive system under test. As mentioned earlier, the impact of multipath contributions on cancellation bandwidth can be assessed with the analysis presented for low-level antenna responses. The level of the multipath component is the value of a, and the physical location corresponds to the point of multipath reflection.

In summary, the facility and instrumentation requirements for adaptive antenna testing are more demanding than those for conventional antenna tests. Future efforts will be required to develop cost-effective facilities and instrumentation for adaptive antenna testing.

D. EVALUATION PARAMETERS

The general goal of adaptive antenna testing is to determine the steady-state loss in system performance caused by the interference and the time from the onset of interference during which the interference is effective. Accordingly, the steady-state performance of the adaptive system and the time

required to converge to that steady-state value must be quantified. This disarmingly simple problem has generated significant confusion. Moreover, an accepted measure of adaptive antenna performance does not exist in the IEEE standards, nor has a commonly accepted terminology or performance definition evolved from the adaptive antenna community. The problem is further compounded by the variability inherent in the interference scenario. In addition, because performance measures are system specific, practical adaptive performance depends on the margin allocated to interference. From a system viewpoint, the effectiveness of the adaptive antenna depends on its ability to recover to acceptable performance, and on the time required to do so, for all of the excursions contained within the interference scenario.

In an adaptive antenna system, three spectral components must be considered: the desired signal, the interference, and the thermal noise. The evaluation of adaptive system effectiveness must measure the changes in all three spectral components. Thus, (1) the modification of the antenna gain over the desired coverage region must be measured to determine loss in desired signal reception with adaptive operation, (2) the reduction in interference power as a result of the adaptive system must be determined over the operating bandwidth, and (3) the increase in total system noise level with adaptive operation must be measured.

The operation of adaptive antenna systems maximizes the SINR, which measures all three spectral components. The SINR is the steady-state output of the adaptive antenna and is commonly used in the adaptive system community. A comparison of the SINR after adaptive operation with the signal-to-noise ratio without interference measures the steady-state loss in system performance caused by the interference. A second related measure compares the SINR after adaptive operation with the SINR before adaptive operation; this comparison measures the improvement in system performance provided by the adaptive cancellation when interference is present. Both performance comparisons have been used by the adaptive antenna community, but with differing terminology.

The SINR can be measured in several ways, and the selection of a method often depends on the system's application. For radar applications a relatively high signal-to-noise ratio is normally required to detect the desired target so that a spectrum analyzer can effectively measure the SINR. A corner

reflector can be effectively used as the desired signal, and can provide a high-level return for accurate measurements. A spectrum analyzer display is also effective in many types of communications applications. For spread-spectrum communication applications, however, the signal, noise, and residual interference levels may not be distinguishable on the spectrum analyzer display; a more accurate measurement of SINR may be inferred from BER (bit error rate) measurements. Finally, the signal, residual interference plus noise, and thermal noise quantities can be measured separately; these quantities are often desired individually for diagnostic reasons.

A typical measurement using a spectrum analyzer proceeds in the following way. The spectrum analyzer is used at the IF level with sufficient preamplification so that the system noise level is unaffected. The system noise and signal components are initially displayed without interference to establish the baseline value. The interference is then added and its level can be calibrated on the spectrum analyzer display. Finally, the adaptive circuitry is activated and the desired signal return and the residual interference power and noise components are displayed. The residual interference power and thermal noise may be displayed in some cases by turning off the desired signal. This display is desirable in examining the variations in residual interference power over the operating bandwidth. In the case of a fully adaptive array, the adaptive weight settings must be fixed so that the array excitation remains at the optimized value for receiving the desired signal.

BER measurements with and without interference provide an accurate way to infer SINR for adaptive systems used with spread-spectrum modems. In this case the desired signal and noise levels may be similar, and a spectrum analyzer display cannot adequately separate the signal components. The measurement proceeds in the following fashion. The modem's performance is initially measured without interference by using an attenuator to vary the signal-to-noise ratio and obtaining the BER performance of the system as a function of signal-to-noise; this measurement calibrates the normal performance of a spread-spectrum modem. The interference is then turned on and its received level is calibrated at the IF level so that the benefits of the modem in rejecting interference do not enter the interference power measurement. The level of the interference can be controlled to produce a level at which the BER performance is usable; this measurement defines the spread-spectrum advan-

tage of the modem in rejecting interference. Finally, the adaptive circuitry is activated and the BER performance is again measured. The level of interference is again controlled to obtain BER values that lie within a usable range. The combined effectiveness of the spread-spectrum modulation and adaptive performance can be quantified on the basis of the maximum interference level for a specified BER. The attenuator for the desired signal can be used to obtain BER values that require a reasonable test time. Present BER instrumentation is typically constructed for specific telecommunications applications; the availability of general-purpose BER instrumentation would extend the usefulness of this test method.

Other measures of adaptive system performance, while useful in diagnostics, fall short of a complete specification of adaptive system performance. Interference cancellation by itself is often quoted as a measure of adaptive system performance. This cancellation measurement can be accomplished in two ways. One method uses a spectrum analyzer display to view just the changes in interference level before and after adaptive cancellation. A second method compares the antenna pattern without interference with an antenna pattern taken with the adaptive weights fixed at their steady-state values. Although this measurement provides the valuable information of antenna gain losses in the desired coverage region, it has unfortunately been used in ambiguous ways. A valid specification of the interference reduction is the difference of the antenna gain in the direction of the interference before and after cancellation. Sometimes, however, the cancellation performance is specified as the ratio of the peak antenna gain to the antenna gain in the direction of interference after cancellation. Moreover, antenna pattern data at a single frequency do not quantify interference cancellation over the required operating bandwidth. While adaptive interference cancellation is a portion of the required evaluation, the changes in the system noise level, adaptive performance over a bandwidth, and antenna gain loss in the coverage area after adaptive operation must also be determined.

Both kinds of antenna measurements as well as the spectrum analyzer measurement have been used to define a "cancellation ratio," and without distinguishing which measurement is used, a quote of achieved "cancellation ratio" results in a situation similar to liar's poker. Moreover, a single number does not reflect the variations of adaptive system performance within

the excursions of a given interference scenario. As the locations of the interference sources vary within the bounds of the scenario, the adaptive system performance also varies. Thus, a single number characterizing the performance of an adaptive antenna design has little meaning.

In general, the total system noise level varies from its value without interference to its value with interference. This variation is more pronounced with sidelobe canceller designs than with fully adaptive arrays. The noise contributions of the auxiliary cancellation element(s) in the sidelobe canceller design are not present in the interference-free case because the adaptive weights are set to zero. When interference is present, however, the noise contributions from this circuitry increase the total system noise level. The total system noise level for the fully adaptive array varies because the array elements combine in a different fashion to cancel interference than they do in the interference-free case. A Y-factor measurement of the total system noise figure[13] can be made to determine differences in the total system noise level. The Y-factor measurement should be made with the adaptive weights fixed at their value without interference, then repeated with their values with interference when possible. The Y-factor measurement with interference is possible in cases in which the noise is injected into the front end of the receiver. Hot and cold load measurements with cold and ambient-temperature absorbers would change the level of the received interference power. These measurements must also be performed with the steady-state adaptive weight values.

The gain loss for desired signals with adaptive operation is another measurement parameter. The spectrum analyzer display can be used to examine the reception of a desired signal; however, this measurement only determines antenna gain loss at a single angular position. In some applications the antenna is required to provide coverage over a specified angular area, and changes in antenna gain with adaptive operation over that coverage area must be measured. Changes in antenna coverage can be particularly pronounced for fully adaptive array designs and adaptive multiple-beam antennas, because these designs, in contrast to sidelobe canceller systems, have the flexibility to alter the antenna pattern within the desired coverage area to minimize interference. Such antenna measurements are made with the adaptive antenna weights fixed at their steady-state adapted values, and should be performed at several frequencies within the required bandwidth.

The time required for the system to achieve adaptive cancellation is the remaining system parameter to be measured. The system objective is to measure the time required for the receiving system to achieve a usable output after the interference is turned on. This measure depends on the system margin allocated to interference degradation, and a specification becomes system specific. In cases when the interference results in loss of lock to the desired signal, the total time the interference is effective includes the time needed to achieve adaptive cancellation, as well as the time needed to re-acquire the desired signal. Finally, in cases in which the interference is strong enough to exceed the capabilities of the adaptive design, the adaptive circuitry will converge to steady-state values, although the system output may not be usable.

Several alternative definitions can be used to define the convergence time of the adaptive circuitry: the time for the adaptive weight values (amplitude and phase) to converge, the time for a specified SINR to be achieved, and the time for the circuitry to recover to a given BER. At the present no universally accepted definition exists for the convergence time, and an appropriate definition depends on the system's application. In addition, the convergence time varies over the excursions of a given scenario.

III. SUMMARY

The measurement of conventional antennas is guided by well-established practices described in an IEEE standard. At present such standards for adaptive antenna testing do not exist, nor has an accepted, consistent terminology evolved from the adaptive antenna community. However, the successful evaluation of adaptive antennas must extend testing from the component values used for conventional antennas to the system level. The extensions of test techniques for adaptive antennas and comparisons with conventional antenna test methods have been discussed with the hope of fostering the further evolution of accepted test procedures.

In comparison with conventional antenna testing, adaptive antenna test results are shown to be more sensitive to the low-level components of the antenna response, such as scattering from the structure surrounding the antenna installation. This increased sensitivity results in more stringent modeling requirements for adaptive antenna measurements than for conventional antenna measurements; similarly, adaptive antenna testing is more sensitive to multipath errors than conventional antenna testing. The simple analysis that demonstrates this sensitivity also highlights the need for including a more realistic representation of the antenna response into analytic projections of adaptive antenna performance; much fruitful research can be done to understand the impacts of the antenna design itself on adaptive antenna processing.

Both adaptive antenna designs and test programs evolve from a scenario that defines the interference environment, a sometimes subjective and time-varying quantity. Analytic projections of adaptive antenna performance for a given scenario are often conducted with Monte Carlo simulations. These simulations, like analytic projections for conventional antennas, can be used to derive test geometries for the interference and limit the required testing to a reasonable time. The resulting experimental validation of the simulation program also increases its usefulness. Adaptive antenna test programs also require more complex instrumentation and test equipment than does conventional antenna testing, as well as measurement facilities capable of generating desired and interference signal components from differing arrival directions. Finally, evaluation parameters for adaptive antenna testing do not have the same level of acceptance as do terms such as "gain" used in conven-

tional antenna testing. A valid definition of adaptive antenna performance quantifies the effects of the adaptive antenna on the signal, interference, and thermal noise components over the required operating bandwidth and excursions of the interference scenario.

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LABORATORY OPERATIONS

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Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and environmental chemistry.

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